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ACCURATE CONTROL TESTING FOR CLAY LINER
PERMEABILITY

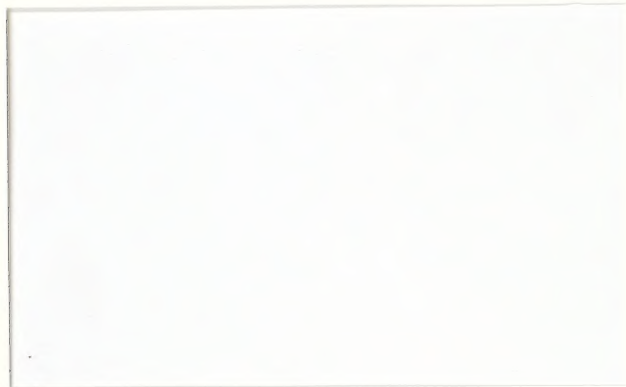
R. A. C. PROJECT NO. 506C



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ACCURATE CONTROL TESTING FOR CLAY LINER
PERMEABILITY

R. A. C. PROJECT NO. 506C

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ABSTRACT

Two series of centrifuge tests were carried out to evaluate the use of centrifuge modelling as a method of accurate control testing of clay liner permeability. The first series used a large 3m radius geotechnical centrifuge and the second series used a small 0.5m radius machine built specifically for research on clay liners. Two permeability cells, which could be easily moved from bench testing to the centrifuge, were fabricated in order to provide direct data comparisons between the two methods of permeability testing. In both cases, the centrifuge method proved to be effective and efficient. The centrifuge method was found to be free of both the technical difficulties and the leakage risks normally associated with laboratory permeability testing of fine grained soils. Two materials were tested, a consolidated kaolin clay having an average permeability coefficient of 1.2×10^{-9} m/s and a compacted illite clay having an average permeability coefficient of 2.0×10^{-11} m/s. Four additional tests were carried out to demonstrate that the 0.5m radius centrifuge could be used for liner performance modelling to evaluate factors such as volumetric water content, compaction method and density, leachate compatibility and other construction effects on liner leakage. The main advantages of centrifuge testing of clay liners, either for design or for construction control, are rapid and accurate evaluation of hydraulic properties and realistic stress modelling for performance evaluations.

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Accurate Control Testing for Clay Liner Permeability
Ontario Ministry of the Environment Project N°506C

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A: EXECUTIVE SUMMARY

A.1: Abstract

Experience with commercial testing of clay liner samples for permeability evaluation has shown that standard laboratory permeability tests are subject to leakage problems which can effect the order of magnitude of the results. Furthermore, these tests typically take a week or more to complete and are, therefore, inadequate as field control tests. Physical modelling of various geo-environmental problems in a geotechnical centrifuge was initiated at Queen's University, Civil Engineering Department, in 1988 and it became apparent that the behaviour of clay liners was one of the problems for which centrifuge modelling was well suited. A dedicated 0.5m radius centrifuge was constructed, principally for long term behavioural studies of clay liners but which could also be used for control testing.

A brief review of liner permeability testing methods and the inherent problems with these methods is presented. The dimensional similitude associated with centrifuge liner modelling and the accelerated real time benefits are also briefly discussed. At a scale factor of 100, for example, one hour of centrifuge modelling is approximately equivalent to one year of prototype liner performance.

The test results are presented in three phases. The first test phase used commercial Kaolin clay samples prepared by consolidation into a specially designed permeability apparatus. This apparatus was designed for both laboratory and centrifuge operation and allowed a direct comparison of the two methods. The centrifuge method was found to be efficient and reliable. The second phase of research used a highly impervious compacted clay liner material and a methodology for accurate clay liner control testing in the centrifuge was developed. The third phase of testing was carried out to examine some longer term permeability variations in compacted liners as a preliminary evaluation of the usefulness of the 0.5 m radius centrifuge for liner performance modelling.

The results of this research shows that a geotechnical centrifuge can be used to provide accurate control testing for clay liner permeability. The 0.5m radius centrifuge can be constructed for about \$10K and is sufficiently mobile for field operations. It can provide a one day result in most practical cases of clay liner permeability testing.

A.2 General Introduction

A number of researchers and consultants have had experience with clay liner permeability testing in the laboratory and in the field and the general consensus appears to be that traditional methods of liner leakage testing are wrought with problems (see for examples, Chapuis, 1990a, 1990b; Quigley, 1990; Mitchell, 1990). Leakage errors in the testing apparatus and the long time required to obtain a satisfactory test result are the two major concerns in laboratory control testing. Field testing is not very useful for hydraulic conductivities less than 10^{-9} m/s. A geotechnical centrifuge offers an alternative, relatively rapid and problem free, method of evaluating clay liner leakage. The major problem with using centrifuge models as a primary means of commercial liner permeability testing has been the limited availability of geotechnical centrifuges in Ontario. To correct this problem, the author has developed a 0.5m radius centrifuge which can be used for mobile testing. This report presents the results of liner leakage testing carried out in this centrifuge. A complete test specification for accurate control testing of clay liner permeability has been developed from this research and is contained in Appendix C.

A.3 Test procedures and Results

The research is divided into three phases.

Phase 1 research was conducted in the 0.5m radius centrifuge using a consolidated commercial white Kaolin clay purchased from Georgia Kaolin Company. The clay was mixed at 100% water content (by dry weight) and consolidated into the permeability testing apparatus. Detailed test procedures are contained in Appendix B.1. The purpose of phase 1 research was to carry out a sufficient number of bench permeability and centrifuge permeability tests on saturated uniform clay samples to determine whether the two methods give similar results. Phase 1 test results are presented in the following section.

Phase 2 research was carried out in the Queen's University 3m radius geotechnical centrifuge and was actually completed prior to the initiation of this contract work. The purpose of phase 2 research was to compare the results of triaxial permeability tests on a relatively impervious compacted clay to liner leakage model testing in a moderate sized geotechnical centrifuge.

Phase 3 research used the same relatively impervious clay, compacted at various moisture contents, to carry out a preliminary evaluation of the 0.5m radius centrifuge for use in modelling the long term field performance of clay liners. Detailed test procedures for phases 2 and 3 are contained in Appendices B.2 and B.3, respectively, and the results are presented in Sections B.2 and B.3 of this report.

Appendix D contains all of the laboratory data from tests carried out under this contract and Section C of this report provides detailed conclusions and recommendations.

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B: TEST METHODS AND RESULTS

B.1: PHASE 1-Evaluation of Centrifuge Liner Permeability Testing

B.1.1 Introduction

Most methods of measuring permeability of soils involve potential variations and errors. Variations develop in the preparation of most soil samples and errors result from equipment leakages. To carry out a meaningful statistical evaluation of the centrifuge method of clay liner permeability it was necessary to develop a leak-proof permeability apparatus in which both bench and centrifuge permeability tests could be carried out under similar conditions on the same samples of a uniform and reproducible clay soil. A saturated consolidated commercial kaolin clay was selected, due to both uniformity and order of magnitude of permeability, as the most suitable clay material. The centrifuge liner leakage model apparatus developed earlier at Queen's University was modified to form the needed permeability apparatus. All phase 1 testing was carried out in the 0.5m radius centrifuge.

B.1.2 Bench Permeability Tests

Detailed procedures for preparing the kaolin material for bench permeability testing and details of the permeability apparatus are contained in Appendix B.1. It is noted that clay samples being tested had been preconsolidated to 250 kPa and that the sample is surrounded by a silicon rubber membrane and a silicon oil pressure seal of 100 kPa during testing to prevent any possibility of leakage. The hydraulic head applied across the 50 mm thick samples was 50 kPa, creating a nominal gradient of 102 and a seepage pressure of about 50 kPa. Over the course of three months, a total of 16 tests were carried out according to the schedule contained in Appendix D. Appendix D also contains the laboratory data sheets from these tests.

B.1.3 Centrifuge Permeability Tests

Appendix B.1 outlines the procedure for doing a centrifuge permeability test on each sample following the bench permeability test. The samples remained in the permeability apparatus during transfer from bench to centrifuge and the boundary stress conditions were similar in each test. The centrifuge induced hydraulic gradient across the sample, however, is 163 and the seepage pressure is 80 kPa. Thus the flow rate in the centrifuge is about 1.6 times faster than in the bench test. Never-the-less, the test conditions in both methods are considered closely similar. The test time in the centrifuge was about 3 to 4 hours compared with 6 to 8 hours in the bench tests. The mass of water in the catchment container was measured after one hour of spinning and again at the end of the test. The one hour check point served the purpose of determining whether any consolidation or other "initial phenomenon" were taking place in the centrifuge. In most cases the N hour mass

transfer was very close to N times the one hour mass transfer. The transfer rate was calculated, for each test sample, in cc/min and the centrifuge permeability was calculated as

$$K = 3.607 \times 10^{-8} \text{ (cc/min) } T_c \quad \text{m/s} \quad (1)$$

where T_c is the temperature correction factor obtained from Appendix C.

B.1.4 Test Results

Figure 1, Appendix A, shows typical volume change vs. time relations for several of the bench tests and the data is summarized on Table 1, Appendix A. It can be noted that the earliest samples, KP 1 to 4 showed relatively high permeabilities because the preconsolidation pressure was below the desired level of 250 kPa. These samples also gave apparent permeabilities from the centrifuge method which are 1.3 to 1.8 times higher than the bench test. This is due, no doubt, to consolidation under the simulated gravitational stresses induced in the centrifuge. In this case that stress is given by

$$\sigma^1_v = z \rho g \lambda + i z \rho_w \quad (2)$$

where z is the sample thickness

g is the gravitational constant

ρ is the sample density

λ is the scale factor (a/g)

i is the induced hydraulic gradient

ρ_w is the density of water

the value of σ^1_v in the centrifuge model is then calculated to be about 120 kPa. The applied confining stress in the early test was 80 kPa and this would also have contributed to sample consolidation. Subsequent samples were all consolidated to a vertical effective stress, σ^1_v , of 250 kPa and a confining stress of 100 kPa was used in subsequent tests. It can be seen from Table 1 that subsequent tests (samples KP5 to KP16) provided a fairly consistent set of permeability data. All test data was plotted, as in Figure 1, to obtain the best fit slope of the line, giving the flow rate (cc/min), and the permeability was calculated as

$$K = 5.774 \times 10^{-8} \text{ (cc/min) } T_c \quad \text{m/s} \quad (3)$$

where T_c is the relevant temperature correction factor as tabulated in Appendix C.

It is important to note that compacted liner samples would be more dense than these consolidated samples such that there would be no consolidation during centrifuge permeability tests on compacted samples.

The data on Table 1 represents an attempt to evaluate the statistical significance of permeability tests. Since the samples varied somewhat in density (likely due to small variations in the mixing and preconsolidation procedures), however, it may not be appropriate to consider these data as a statistical set of identical samples. It is, however, useful to compare the mean and deviation of each test method. The means and standard deviations (assuming a normal distribution) are as follows:

<u>Test method</u>	<u>Mean K , m/s</u>	<u>Std. deviation</u>
Bench test	1.21×10^{-9}	0.22×10^{-9}
Centrifuge test	1.46×10^{-9}	0.57×10^{-9}

If tests KP1 to KP4 are eliminated on the grounds that sample consolidation might have effected the results, the results are as follows:

<u>Test method</u>	<u>Mean K , m/s</u>	<u>Std. deviation</u>
Bench test	1.15×10^{-9}	0.10×10^{-9}
Centrifuge test	1.20×10^{-9}	0.09×10^{-9}

These data indicate that, for these consolidated samples, the centrifuge test gives a marginally higher value of permeability and a similar variance as the bench test. Of much greater significance, of course, is the conclusion that the 0.5m centrifuge can be used effectively and efficiently to evaluate the permeability coefficient (hydraulic conductivity) of a consolidated clay material.

B.2: PHASE 2-Control Leakage Testing of a Compacted Clay Liner

B.2.1 Introduction

Geotechnical consultants are faced with the task of evaluation clay liner leakage by control testing of compacted materials having hydraulic conductivities as low as 10^{-11} m/s. Standard methods for such control testing include falling head permeability testing on a sample compacted in a mold and triaxial constant head permeability testing. Edge leakage in the former and membrane or connection leakages in the latter of these tests can be a significant problem. For example, at $k = 10^{-11}$ m/s, an hydraulic gradient of 25 would produce less than 0.5 cc/day of flow through a 50 mm diameter triaxial sample. This is about equal to the membrane leakage in ordinary triaxial testing and, thus, special methods must be used to reduce membrane leakage. The need to backpressure during laboratory permeability testing, in order to ensure sample saturation, increases the risk of leakage and renders test results suspect. Even if all leakage is eliminated, a typical test takes one to two weeks to complete; hence control testing lags behind construction. This makes remedial action more costly if the results do not meet the specifications. There is, clearly, a need to develop standards for liner leakage evaluation and to study new methods of performing more accurate and less time consuming liner control testing. A geotechnical centrifuge model test procedure offers one possible solution to the current problems of leakage evaluation with very low permeability clay liners.

B.2.2 Triaxial Permeability Tests

Either laboratory compacted or field compacted liner materials can be trimmed and fitted into a standard triaxial cell equipped with back pressured burette systems for carrying out permeability testing. The earliest of such systems is described in Bishop and Henkel (1962) and the latest of such systems, equipped with electronic monitoring, are found in the better commercial laboratories. The test procedure is briefly outlined in Appendix B.2. Figure B.5, Appendix B, shows a typical experimental arrangement. All of these systems share the common problem of leakage. There are two valves, six line connections outside the cell and two line connections inside the cell of a typical back pressured permeability testing arrangement - all are potential leakage locations. The highest probability of connection leakage, however, is associated with the drainage connection inside the cell which must be disconnected and connected each time a new sample is installed.

Membrane leakage and, despite tight O-ring seals, leakage between the membrane and the end platens is a second source of leakage. When doing permeability testing it has become fairly standard practice to use double membranes with a thick smear of silicon grease between these. This does not solve the membrane-platen

leakage problem.

The final problem with the triaxial permeability test for use in liner control testing is the long time required to obtain an experimental result. If control samples are taken from a liner as it is being compacted in the field, the contractor would like to know immediately whether the design criterion is being met. To have to wait two weeks for a control test result makes day to day decision making most difficult. In addition, it is difficult to know whether variations in control test results are due to variations in materials or methods or are due to problems with the test procedure.

B.2.3 Triaxial Test Results

In order to evaluate the use of triaxial permeability testing, a geotechnical laboratory technician with ten years of experience at soils testing was asked to compact and carry out double membraned back pressured permeability testing on a local illite clay material. A Standard Proctor compaction test on this clay gave a dry density of 1.37 g/cc at an optimum water content of 35.5%. The material was stored at this water content and was subjected to Standard Proctor compaction to form samples which were subsequently trimmed for permeability testing. After testing the used materials were remixed with the original batch and stored for further testing. Two triaxial cells with back pressured systems were newly assembled, platens were polished and leakage testing of the systems was carried out before the permeability testing was begun. In total, six acceptable tests were carried out over a two month period. This is an average of less than two tests per cell-month, mainly because the system required considerable attention and repair during that time period.

The results of the triaxial permeability testing are contained in Table 2 of Appendix A. All samples for which results are tabulated were backpressured to 300 kPa and subjected to an hydraulic gradient of 40. This laboratory testing was carried out at 20°C. From the data it is estimated that the mean permeability value is close to 2.3×10^{-11} m/s with individual test values from 0.3 to 1.3 times the average value. For material evaluation, this data seems reasonably acceptable although the scatter is quite significant.

Looking more closely at some of the data creates causes for concern. Figure 2 shows the data from three tests. Test LPTX1 was started after 24 hours under a 200 kPa backpressure. Because the data points from the inflow and outflow burettes appear to correspond closely, it is very surprising to learn that, in fact, both burettes appeared to be delivering water into the sample (i.e. the outflow burettes differentials are negative). Is it possible that considerable air was trapped in the system and it takes more than eight days to entrain this air at a back pressure of 200 kPa? Or, alternatively, is it more likely that the outflow system was leaking at some connection? Water could not be observed at any connections but, at this slow leakage rate, evaporation could steal

the evidence. Who knows?

Test LPTX6 on Figure 2 appears to be one of the better tests because it gives a balanced result. In all tests, the idea of independent measurement of inflow and outflow is to try and delineate the effects of leakage. In our tests the outflow burette usually indicated a higher flow rate than the inflow. Is the outflow erroneously high due to inside connection or membrane leakage? Is the inflow erroneously low due to air entrainment or membrane leakage? Does the average flow rate of 0.12 cc/day really represent the material permeability? If it does, how are the results of test LPTX2 and LPTX5 explained? Can there really be that much permeability variation or preparation variability in this fairly homogeneous remoulded material or did these tests suffer from leakage problems? Clearly there are more questions than answers when one examines the data from triaxial permeability testing. It is also clear that the confidence level in the result from a single control test would not be very high.

B.2.4 Centrifuge Liner Leakage Models

A prototype clay liner will be overlain by landfill materials which may become saturated with liquids and, over a long period of time, liner leakage may occur. This worse case condition (or any other operational condition) can be modelled in the geotechnical centrifuge. The total and effective stresses at all similar points in the model and prototype liners will be identical but the hydraulic gradient across the model liner will be increased by the modelling scale factor. If, for example, a prototype liner of 2m thickness is supporting an overlying head of water of 20 m, the hydraulic gradient is 10. If a model is designed at a scale factor of $\lambda = 35$, the 57 mm thick model would then have an hydraulic gradient of 350 and one day of testing in the centrifuge at $\lambda = 35$ would produce λ^2 days or 3.35 years of prototype per unit area leakage. The major assumption in this type of modelling is that the same physical phenomenon will take place at gradients of 10 and 350. It is known that Darcy's Law, $v = ki$, is not rigorously applicable to all flow through porous media and that the flow may be accelerated by large gradients, particularly in coarse grained soils. In fine grained soils it is unlikely that the error will be significant (Goodings, 1985).

The procedure for centrifuge testing is briefly outlined in Appendix B.2. Figure B.7 shows the apparatus developed for liner modelling. The liner model is nominally 50 mm thick, and is trimmed to fit snugly in a double thickness membrane encased perspex ring. The overlying landfill materials are simulated by a known mass of lead shot overlying a porous plastic disk placed on the top of the liner model. Double thickness filter paper and a porous stone underly the model. Stand pipe arrangements are used to create the water pressure and the confining pressure, which both increase as the simulated gravitational force increase in flight. The confining pressure is maintained at 35 kPa above the water pressure in order to effect a tight contact between the liner model and the rubber

membrane.

Prior to carrying out a liner leakage model test, the model is conditioned in-flight and any water extruded under this conditioning process is removed from the catchment container prior to the liner permeability test run. A model with $C_v = 0.3 \text{ m}^2/\text{yr}$ would require approximately 20 hours of complete primary consolidation in the laboratory but the process is speeded up by a factor λ^2 in the centrifuge. At $\lambda = 35$ it requires only a few minutes to complete primary consolidation. Never-the-less, models were conditioned in-flight for 30 to 60 minutes before liner leakage model testing. Table B.1, Appendix B, lists the conditions under which the liner leakage model tests presented in this paper were carried out.

Liner leakage model tests were carried out over periods varying from five hours to ten hours. During some tests the centrifuge was stopped every two hours to check the mass transfer of water by weighing the catchment container ($\pm 0.005 \text{ g}$). Mass transfer quantities were in the order of 0.1 g/hr and the variance found during the two hour interval tests was generally less than 20%. Table 3, Appendix A, shows the data from all of the centrifuge liner leakage model tests carried out. With two identical model containers mounted in the same centrifuge strongbox it was possible to complete two model tests per day.

The average leakage rate, from the data on Table 3, is 0.10 cc/hr with a maximum individual test variance of 20%. The water temperature in the liner model apparatus increased 2.5° C above the constant laboratory temperatures of 20° during the first hour or two of spinning at 108 RPM and then remained constant throughout the remainder of the test. The calculated coefficient of permeability, from the average leakage rate is $2.2 \times 10^{-11} \text{ m/s}$. With standard temperature correction, the hydraulic conductivity is estimated to be $2.0 \times 10^{-11} \text{ m/s}$. This average is remarkably close to the average from the triaxial permeability testing but the centrifuge data is much more consistent than the triaxial, providing some confidence in individual liner control tests carried out by centrifuge modelling.

B.2.5 Conclusions

From the test data reported, it is concluded the centrifuge model liner leakage testing gives more consistent results for a low permeability compacted soil than triaxial permeability testing. The latter testing is subject to both technical difficulties and leakage risks. It is tentatively concluded that a centrifuge liner leakage model can provide realistic liner performance evaluation and that the hydraulic conductivity obtained from such a model will be closely similar to the average values found from good quality triaxial permeability testing.

The main advantages of centrifuge liner leakage models are:

- (1) Realistic modelling of stress conditions in the liner so that the risks of consolidation or hydraulic fracturing during testing are eliminated .
- (2) Elimination of connection leakage provides more consistent results.
- (3) Rapid evaluation for control testing during liner construction.
- (4) Greater flexibility and potential for modelling liner performance evaluations.

A standard strongbox for model testing on the Queen's geotechnical centrifuge can accommodate up to four liner model containers. Both ends of the radius arm are capable of carrying strong boxes. Therefore, eight liner leakage model control tests can be carried out in one day. This would reduce the cost of each centrifuge liner permeability model to less than the cost of a triaxial permeability test. Centrifuge modelling can be a cost-effective method of evaluating clay liner permeability.

B.2.6 References

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B.3: PHASE 3 - Preliminary Evaluation of Field Performance

B.3.1 Introduction

Clay liners are compacted in the field at a specified (or achieved) water content. There will be field variations in leakage rates and other performance factors due to variations in compaction water content and compaction effort. It is important to recognize and evaluate these variations. If field samples are back pressure prior to permeability testing, these variations will be at least partially eradicated. A geotechnical centrifuge offers the alternative of field evaluations of samples obtained as compacted. In order to demonstrate the possible variations, four samples of the relatively impervious illitic clay were compacted, two at 30% water content and two at 40% water content, and subjected to liner leakage modelling in the 0.5m radius centrifuge.

B.3.2 Test Methodology

Compacted clay samples were mounted in the liner leakage modelling apparatus (Figure B.7) with an applied surcharge of 3cm of lead shot. Testing was carried out according to the procedure described in Appendix C. The relevant conditions were: oil pressure surcharge of 50 kPa and centrifuge speed of 300 rpm giving a scale factor of 40 and a head pressure of 60.5 kPa. The models represented prototype liners of $40(0.05) = 2\text{m}$ thickness with an overlying saturated fill material of 6.2m thickness and 1.33t/m^3 dry density. Measurements of water inflow and water outflow were taken every hour over the course of six to eight hours of modelling. At this scale factor of 40, eight hours of modelling represents about 1.5 years of prototype leakage. Inflow water was gauged by the mass of water required to refill the reservoirs at each test interval.

B.3.3 Test results

The data from tests CC 1/2 and CC 3/4 are included in Appendix D and the results are shown graphically in Figure 3, Appendix A. Figure 3 shows inflow and outflow rates against real time. The model leakage rate (cc/hr) is multiplied by an area factor, $24,000 \text{ ft}^2/28.3 \times 10^{-4} = 136$ to obtain a prototype leakage rate in litres/ m^2 .day. It is noted that the leakage rate predicted from models CC 3/4 is fairly constant with time and that the inflow is essentially equal to the outflow. This is indicative of a saturated sample. Models CC 1/2 were not saturated but the data indicates that the degree of saturation, hence the leakage rate, increased throughout the model test. There is a significant difference between the leakage rates associated with two compaction water contents for two reasons: the increased water content produced, for the same Standard Proctor compaction effort, a decreased density and increased saturation. Both of these changes produce greater leakage. These results demonstrate the importance of adequate field control of placement conditions.

B.3.4 Discussion and Conclusions

The results of four tests carried out as Phase 3 of this research demonstrate quite clearly that taking field samples to a laboratory for standard back pressured permeability testing may not yield correct leakage evaluations. The alternative of laboratory or field control testing using a dedicated centrifuge would provide more rapid and more realistic evaluations. Centrifuge liner modelling would also facilitate the evaluation of contaminant migration through clay liners.

C: SUMMARY CONCLUSIONS AND RECOMMENDATIONS

C.1 General Summary

The research reported under this contract is divided into three phases - a statistical evaluation of centrifuge liner permeability testing; a comparison of triaxial permeability testing and centrifuge liner leakage modelling; a preliminary evaluation of liner performance modelling. The 0.5m centrifuge, developed specifically for clay liner modelling, is described for the first time in this report. Clearly this work has shown that this centrifuge is an effective and efficient tool for clay liner permeability (leakage) evaluation. The work also indicates quite strongly that there may be significant differences between liner performance predictions from back pressured triaxial testing and actual compacted prototype liner performance. Equipment and a specification for clay liner permeability testing in a geotechnical centrifuge have been developed.

C.2 General Conclusions

The reported comparative testing and evaluations have produced the following conclusions:

- (1) The 0.5m radius centrifuge is an efficient and effective tool for measuring the permeability of stiff clay samples.
- (2) The use of the centrifuge for clay liner leakage evaluation offers the advantages of accuracy, speed and ease of operation. The 0.5m radius centrifuge is self-contained and sufficiently mobile to be used in the field.

- (3) Centrifuge modelling of liner performance offers the further advantage of correctly modelling the prototype effective stress regime throughout the liner history so that other factors which may affect performance (contaminants, etc) can be studied under these stress conditions.

Centrifuge modelling can, no doubt, contribute further to the very important task of evaluating the long term performance of compacted clay liners using accelerated modelling techniques.

C.3 Recommendations

It is recommended that the 0.5m centrifuge be further evaluated as a method of liner permeability testing by using it on a field site in parallel with current methods. It is also recommended that the research potential of centrifuge liner performance modelling be further supported with the longer term goal of using this tool to study the effects of various contaminants on liner performance for various clay types.

Appendix A	Tables and Figures
A.1	Tables 1 to 3
A.2	Figures 1 to 3

Sample No	Saturated density g/cc	BENCH TEST		CENTRIFUGE TEST	
		test time min.	hydraulic conductivity m/s x 10 ⁻⁹	test time min.	hydraulic conductivity m/s x 10 ⁻⁹
KP1	1.82	450	1.46	180	2.65
KP2	1.81	450	1.65	180	3.05
KP3	1.84	810	1.10	210	1.58
KP4	1.88	810	1.35	210	1.73
KP5	1.91	480	1.12	240	1.13
KP6	1.90	480	1.05	240	1.14
KP7	1.95	420	0.96	180	1.06
KP8	1.87	420	1.27	180	1.27
KP9	1.90	420	1.27	180	1.37
KP10	1.86	420	1.18	180	1.19
KP11	1.87	450	1.21	240	1.30
KP12	1.92	450	1.10	240	1.21
KP13	1.88	1100	1.28	180	1.23
KP14	1.94	1100	1.11	180	1.12
KP15	1.86	465	1.15	180	1.24
KP16	1.89	465	1.15	180	1.11

TABLE 1 - PHASE 1 TEST RESULTS SUMMARY

Test Designation	Test time (days)	Inflow c/day	Outflow cc/day	Average flow cc/day	Hydraulic conductivity $k = m/s$
LPTX1	8	0.26	-0.24	neg.	n/a
LPTX2	9	0.32	0.40	0.36	3.3×10^{-11}
LPTX3	8	0.12	0.06	0.09	0.8×10^{-11}
LPTX4	7	0.08	0.12	0.10	0.9×10^{-11}
LPTX5	8	0.30	0.86	0.58	5.3×10^{-11}
LPTX6	12	0.10	0.14	0.12	1.1×10^{-11}

TABLE 2 - PHASE 2 TRIAXIAL RESULTS

Test Designation	Test time (hours)	Leakage rate (cc/hr)	Hydraulic conductivity $k = m/s$
LPCM1	5	0.091	2.0×10^{-11}
LPCM2	7	0.103	2.2×10^{-11}
LPCM3	8	0.102	2.2×10^{-11}
LPCM4	6	0.122	2.6×10^{-11}
LPCM5	10	0.082	1.8×10^{-11}
LPCM6	8	0.118	2.5×10^{-11}

TABLE 3 - PHASE 2 CENTRIFUGE RESULTS

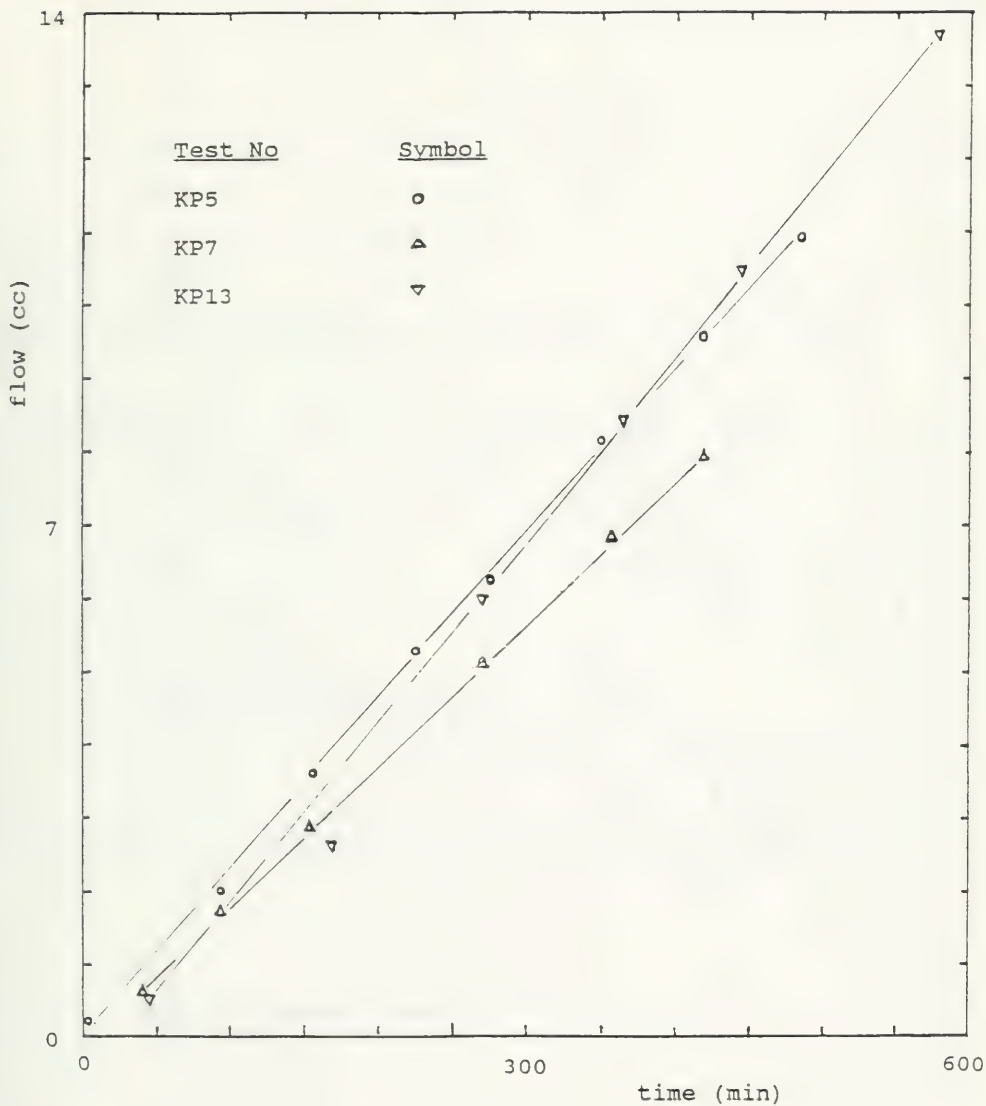


FIGURE 1 - TYPICAL FLOW RATES IN BENCH TESTS

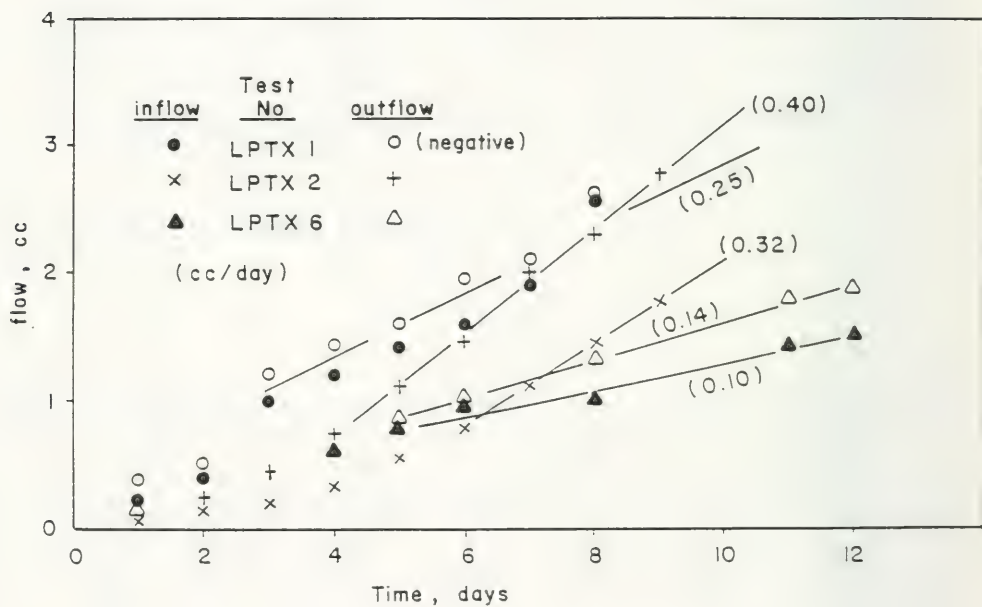


FIGURE 2 - TYPICAL TRIAXIAL PERMEABILITY DATA

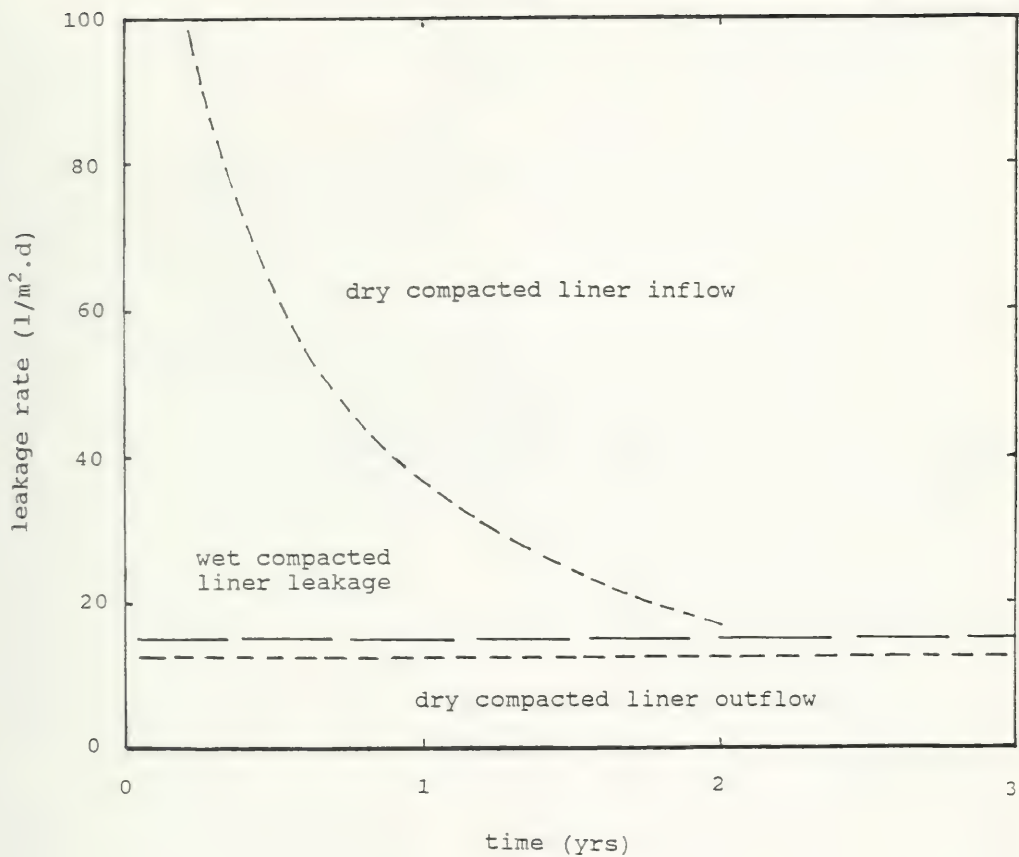


FIGURE 3 - PHASE 3 COMPACTED LINER LEAKAGE DATA

- Appendix B Test Procedures
- B.1 Phase 1: Permeability Measurement
 in the Centrifuge
 - B.2 Phase 2: Triaxial vs. Centrifuge
 Measurements of Liner Leakage
 - B.3 Phase 3: Long Term Liner Performance
 Measurement in the 0.5m Centrifuge

B.1 - Phase 1: Permeability measurement in the centrifuge

Purpose - to demonstrate that the 0.5m centrifuge can be used to make accurate permeability measurements on a saturated preconsolidated clay.

Apparatus and test procedure - Phase 1 tests were carried out as duplicate pairs and the apparatus shown on Figure B.1 is one of the pair used to carry out the Phase 1 testing as follows:

- Step 1 - a 1mm thick silicon rubber membrane is placed on the sample container ring and the pressure cavity is wetted with silicon oil and subsequently evacuated such that the membrane is tightly held to the perspex ring.
- Step 2 - the base plate, container ring, consolidation extension (lightly coated with silicon grease) and collar are assembled and a thin porous geotextile disk is placed above the base porous stone (previously deaired).
- Step 3 - previously mixed Kaolin clay slurry at $w = 100\%$ is used to fill the sample ring and extension to the desired level and a porous geotextile disk and porous stone are placed on the poured sample. The poured sample is shown in Figure B.2.
- Step 4 - a mass hanger assembly is used to consolidate the clay slurry, over a four day period, to a vertical stress level of 250 kPa. At this stress level, the consolidated sample is nominally 55mm in height and is mainly contained within the sample container ring.
- Step 5 - after removal of the mass hanger and consolidation extension, the sample is trimmed to 50mm in height and a filter paper and top plate is placed on the sample and tightened onto the container ring. The outflow catchment container is fixed to the base plate drainage port. An inflow burette is attached to the top plate port and a bench permeability test is carried out. During the test the silicon oil pressure in the pressure cavity (the confining pressure) is maintained at the estimated at rest lateral pressure of 100 kPa and a head pressure of 50 kPa is used to create water flow through the samples (50 kPa gives an hydraulic gradient of approximately 100 across the sample). The laboratory bench permeability test was carried out over time periods of up to 8 hours, with burette readings at appropriate time intervals. The bench tests are shown on Figure B.3. The mass of water in the outflow catchment containers is measured at the end of the tests.

Step 6 - following the bench permeability tests, the two samples are mounted in the centrifuge. Figure B.4 shows a sample container in the centrifuge. To move from the bench permeability tests to the centrifuge requires the disconnection and reconnection of the water pressure supplies. Pressures in the centrifuge are supplied by the centrifugal forces acting on fluid columns (note that the columns are horizontal, aligned with the direction of the simulated gravitational forces). Testing was carried out at 300 rpm, giving a simulated acceleration at mid-sample level of 40 gravities and a head pressure of 61.3 kPa (hydraulic gradient = $125 + 1 = 165$). A rubber bladder contained in the centrifuge beam maintained an air pressure of 50 kPa on the silicon oil column such that the confining pressure, at 300 rpm was 100 kPa. The centrifuge speed was maintained at 300 rpm for a period of between two and four hours. At the end of the test run, the outflow catchment container was weighed to obtain the mass of the drainage water.

It is important to note that there are no potential sources of water leakage between the top of the sample and the outflow catchment container such that all water found in that container passed out of the clay sample. The clay sample was weighed at the end of the centrifuge test and the phase properties were determined. Detailed procedures for conducting a liner permeability test in the 0.5m centrifuge are given in Appendix C.

B.2 - Phase 2: Traxial vs. centrifuge measurements of liner leakage

Purpose - to compare centrifuge liner leakage evaluations with data from conventional traxial permeability tests.

Triaxial apparatus and test method - Phase 2 tests were carried out in pairs using a compacted natural clay material. Two standard traxial permeability test cells (see Figure B.5) and standard procedures were used to carry out the traxial permeability tests (see, for example, Bishop and Henkel, 1962). These tests required several days due to the very low permeability of the compacted materials. A brief description of the procedure follows:

Step 1 - the clay liner material was subjected to standard Proctor compaction at its optimum water content of 35.5%. Test samples were trimmed to the standard 50 mm diameter by 60 mm in height and were

mounted in the triaxial permeability apparatus. The samples were consolidated and back pressured for 24 hours under a cell pressure of 450 kPa and a back pressure of 300 kPa.

Step 2 - after 24 hours the back pressure was lowered by 10 kPa and the head pressure was increased by 10 kPa to create an hydraulic gradient of about 40 across the sample. These conditions were maintained for eight to ten days, during which time both the inflow burette (under head pressure) and outflow burette (under back pressure) were read two or three times per day. Permeability values were calculated from the average flow rate $(\text{inflow rate} + \text{outflow rate})/2$, providing these were closely similar (indicating that joint or membrane leakage was unlikely).

Step 3 - test samples were removed and subjected to moisture content and density determinations.

Centrifuge testing procedure - Phase 2 centrifuge tests were carried out in Queen's University 3m radius centrifuge (see Figure B.6). Samples were trimmed, from compacted clay, at 35.5% water content, to 60 mm diameter by 50 mm height and were placed in the centrifuge liner leakage containers (see Figure B.7). Both containers were mounted on one end of the radius arm and balance masses were placed on the other end. Water and silicon oil pressures were provided by radial columns so that the stress conditions on the samples were as noted on Table B.1. The samples were accelerated at 35g for between 6 and 8 hours at which time the mass of water in the catchment containers was determined by weighing to $\pm 0.005\text{g}$. The permeability is calculated and corrected for temperature.

General Conditions:

Model liner dimensions: diameter = 61 mm, height = 48 mm

Model scale factor $\lambda = 35$ obtained at 108 RPM

Prototype liner thickness = $\lambda(48 \text{ mm}) = 1.7 \text{ m}$

Induced hydraulic gradient in model = 420

Stress Conditions	Top of Model	Bottom of Model	Average
Effective stress, σ_v due to lead shot and model masses	250 kPa	280 kPa	265 kPa
Water pressure, u due to 0.58 m water head	200 kPa	0	100 kPa
Total stress, σ_v	450 kPa	280 kPa	365 kPa
Seepage stress, p_s due to gradient	0	200 kPa	100 kPa

Table B.1 Stress Conditions in 3m Centrifuge

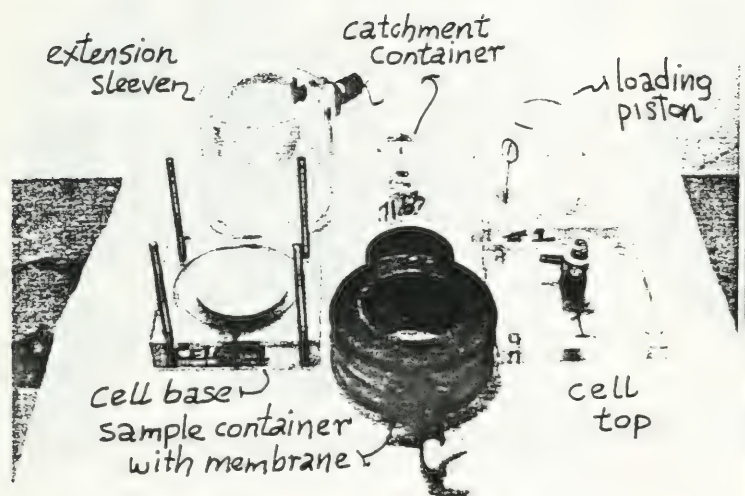


FIGURE B.1 BENCH PERMEABILITY APPARATUS



FIGURE B.2 POURED SAMPLE BEFORE
 CONSOLIDATION

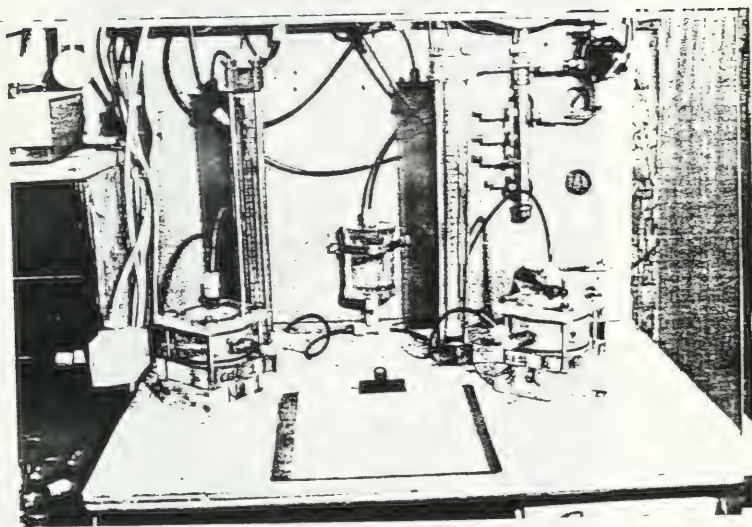


FIGURE B.3 BENCH PERMEABILITY TESTS



(a) top
view

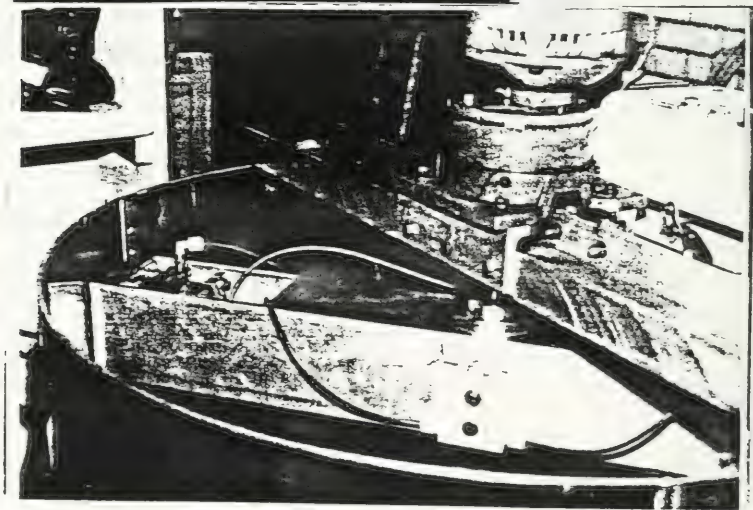


FIGURE B.4 SAMPLE CONTAINER IN CENTRIFUGE

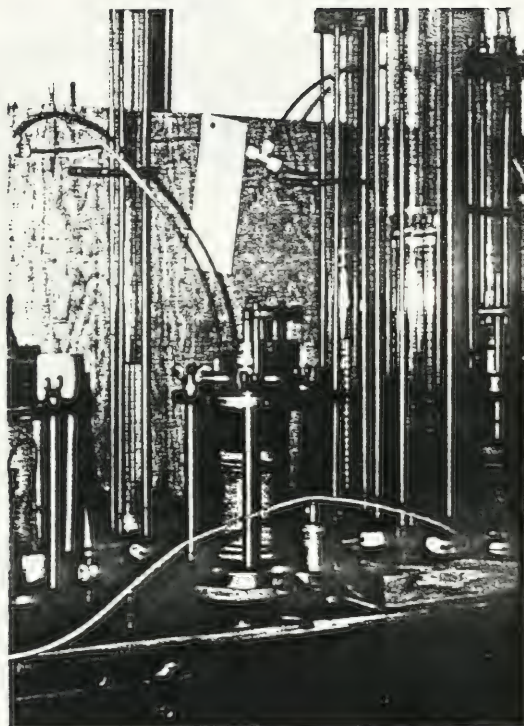


FIGURE B.5 STANDARD PERMEABILITY CELLS

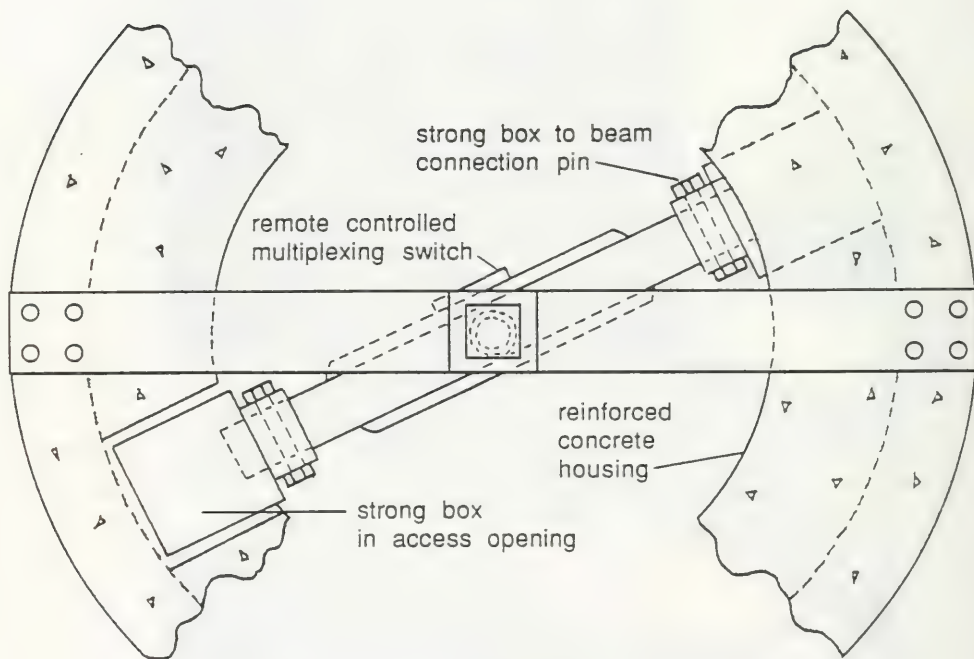
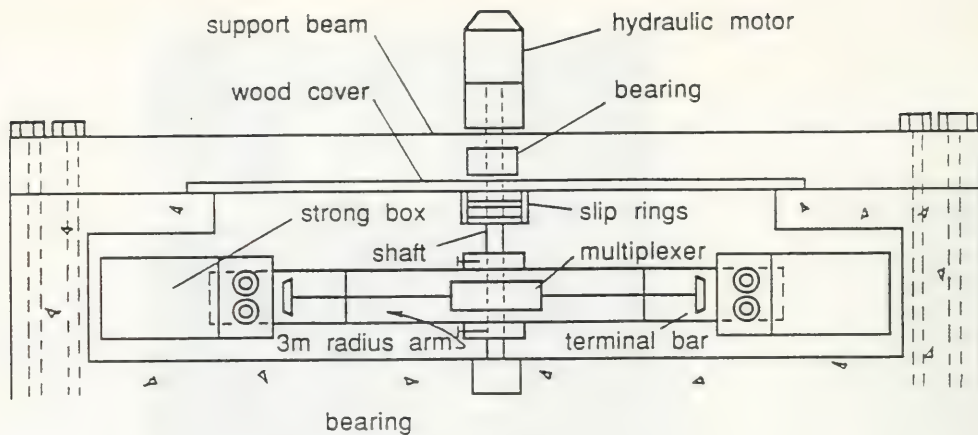
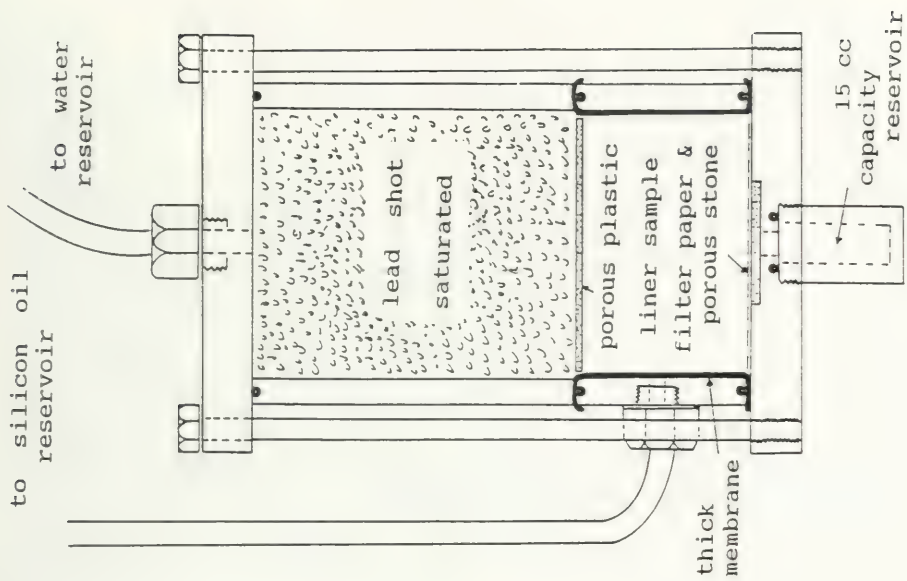


FIGURE B.6 QUEEN'S 3m GEOTECHNICAL CENTRIFUGE



(a) photograph

(b) diagram showing parts

FIGURE B.7 LINER MODELLING APPARATUS

Appendix C Test Specification for Liner Leakage
Control Testing in the 0.5m Centrifuge

Appendix C - Procedure for liner sample permeability testing in the 0.5m radius centrifuge

The following steps are employed in carrying out a liner sample permeability test in the small centrifuge which has an operating radius of 0.35m between the water reservoir (at $r=0m$) and the top of the sample (at $r=0.35m$):

- Step 1 - two samples are mounted in the two liner permeability test apparatuses either (a) directly from bench tests as shown on Figure B.3 or (b) compacted with a surcharge loading¹ as shown in Figure B.7. The masses of the containers are obtained and mass is added, as needed, to balance the two packages.
- Step 2 - the oil and water reservoirs in the centrifuge are filled and connections are made to the apparatuses as they are installed. Valves to the samples are closed at this stage.
- Step 3 - the central air bladder, which is connected to the silicon oil reservoir, is inflated to the desired pressure (40 kPa to 60 kPa). The oil valves and water valves are opened to the sample test apparatuses.
- Step 4 - the centrifuge is accelerated to the required speed (usually between 300 and 500 rpm) to provide a scale factor between 40 and 112 and is run for 1 hour or 2 hours depending on the expected permeability and duration of test, as shown on Table C.1. Figure C.1 is a typical data entry sheet.
- Step 5 - the centrifuge is stopped and the mass of the water in the catchment containers is determined. Reservoir levels are checked. A permeability estimate is made from this result.
- Step 6 - the catchment containers are replaced and the centrifuge is run continuously at the same speed for the required duration (usually 2 to 24 hours), as determined from Table C.1 and checked by the result in Step 5. For example, with a low permeability of $k = 5 \times 10^{-10}$ m/s a test could be run at 450 RPM for 10 hours to give a total mass transfer (flow) of about 20 cc of water. Temperature readings are checked during this time period to obtain the average temperature for the test run.

1. The surcharge load is designed to simulate the stress applied to the liner by overlying landfill materials in the prototype situation. Contaminants can be included in this surcharge to evaluate their effects on the liner performance.

Step 7 - the catchment containers are retrieved for water mass determinations and the samples are removed for phase determinations.

Step 8 - the sample permeability is calculated as outlined in Table C.2.

Centrifuge speed RPM	Induced hydraulic gradient	expected flow rate cc/hr for		
		$k = 10^{-8}$ m/s	$k = 10^{-9}$ m/s	$k = 10^{-10}$ m/s
300	165	17	1.7	0.17
350	223	22	2.2	0.22
400	291	30	3.0	0.30
450	358	36	3.6	0.36
500	455	46	4.6	0.46

Table C.1 Centrifuge Speed and Flow Rates

Sample area = A = 28.3 cc; sample height = H = 5 cm

Test speed = RPM ; gradient $i = \frac{6.717 \times 10^{-4} (\text{RPM})^2}{981 (H)}$

Test duration = t hr ; total mass transfer (flow) = Q cc

Permeability coefficient = $\frac{Q/t}{i A}$ cm/hr (divide by 3.6×10^{-5} to obtain

m/s). Multiply by the relevant temperature coefficient from Table C.3 to obtain corrected permeability.

Example: $i = 455$, $Q = 25$ cc , $t = 10$ hours, $T = 27^\circ\text{C}$ ($T_c = 0.85$)

$k = (25/10)/(455) 28.3 = 1.94 \times 10^{-4}$ cm/hr = 5.4×10^{-10} m/s

$K \text{ corr.} = 5.4 \times 10^{-10} \text{ m/s} (0.85) = 4.6 \times 10^{-10} \text{ m/s}$

Table C.2 Permeability Calculations

°C	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
10	1.3012	1.2976	1.2940	1.2903	1.2867	1.2831	1.2795	1.2759	1.2722	1.2686
11	1.2650	1.2615	1.2580	1.2545	1.2510	1.2476	1.2441	1.2406	1.2371	1.2336
12	1.2301	1.2268	1.2234	1.2201	1.2168	1.2135	1.2101	1.2068	1.2035	1.2001
13	1.1968	1.1936	1.1905	1.1873	1.1841	1.1810	1.1777	1.1746	1.1714	1.1683
14	1.1651	1.1621	1.1590	1.1560	1.1529	1.1499	1.1469	1.1438	1.1408	1.1377
15	1.1347	1.1318	1.1289	1.1260	1.1231	1.1202	1.1172	1.1143	1.1114	1.1085
16	1.1056	1.1028	1.0999	1.0971	1.0943	1.0915	1.0887	1.0859	1.0803	1.0802
17	1.0774	1.0747	1.0720	1.0693	1.0667	1.0640	1.0613	1.0586	1.0560	1.0533
18	1.0507	1.0480	1.0454	1.0429	1.0403	1.0377	1.0351	1.0325	1.0300	1.0274
19	1.0248	1.0223	1.0198	1.0174	1.0149	1.0124	1.0099	1.0074	1.0050	1.0025
20	1.0000	0.9976	0.9952	0.9928	0.9904	0.9881	0.9857	0.9833	0.9809	0.9785
21	0.9761	0.9738	0.9715	0.9692	0.9669	0.9646	0.9623	0.9600	0.9577	0.9554
22	0.9531	0.9509	0.9487	0.9465	0.9443	0.9421	0.9399	0.9377	0.9355	0.9333
23	0.9311	0.9290	0.9268	0.9247	0.9225	0.9204	0.9183	0.9161	0.9140	0.9118
24	0.9097	0.9077	0.9056	0.9036	0.9015	0.8995	0.8975	0.8954	0.8934	0.8913
25	0.8893	0.8873	0.8853	0.8833	0.8813	0.8794	0.8774	0.8754	0.8734	0.8714
26	0.8694	0.8675	0.8656	0.8636	0.8617	0.8598	0.8579	0.8560	0.8540	0.8521
27	0.8502	0.8484	0.8465	0.8447	0.8428	0.8410	0.8392	0.8373	0.8355	0.8336
28	0.8318	0.8300	0.8282	0.8264	0.8246	0.8229	0.8211	0.8193	0.8175	0.8157
29	0.8139	0.8122	0.8105	0.8087	0.8070	0.8053	0.8036	0.8019	0.8001	0.7984
30	0.7967	0.7950	0.7934	0.7917	0.7901	0.7884	0.7867	0.7851	0.7834	0.7818
31	0.7801	0.7785	0.7769	0.7753	0.7737	0.7721	0.7705	0.7689	0.7673	0.7657
32	0.7641	0.7626	0.7610	0.7595	0.7579	0.7564	0.7548	0.7533	0.7517	0.7502
33	0.7486	0.7471	0.7456	0.7440	0.7425	0.7410	0.7395	0.7380	0.7364	0.7349
34	0.7334	0.7320	0.7305	0.7291	0.7276	0.7262	0.7247	0.7233	0.7218	0.7204
35	0.7189	0.7175	0.7161	0.7147	0.7133	0.7120	0.7106	0.7092	0.7078	0.7064

Table C.3 Temperature Correction Factors

QUEEN'S UNIVERSITY DEPARTMENT OF CIVIL ENGINEERING

CENTRIFUGE PERMEABILITY TESTS

Date _____

Technician _____

Centrifuge Operating Radius _____ m

Material Description: _____

Sample height	_____ cm	Tare	_____ g
Sample area	_____ cm	W+T	_____ g
Sample volume	_____ cc	D+T	_____ g
Confining pressure	_____ kPa	WW	_____ g
Head pressure	_____ kPa	W	_____ %
Centrifuge Speed	_____ rpm	Density	_____ g/cc

Time	ΔT min	Sample No 1		Sample No 2	
		mass transfer cc	t °C	mass transfer cc	t °C

SUMMARY:

Centrifuge speed	_____ RPM	Induced pressure	_____ kPa
Temperature (avg.)	_____ °C	Time of test run	_____ hrs
Quantity of flow:	Sample 1 _____ cc;	Sample 2	_____ cc
Coefficient of permeability	_____ m/s		
Temperature correction factor	_____		
Corrected hydraulic conductivity	_____ m/s		

Figure C.1 - Data entry sheet for centrifuge permeability test

Appendix D Laboratory Data

DATE	MONDAY	TUESDAY	FRIDAY	COMMENTS
2 July	Installation of equipment in laboratory			
9 July	Testing of bench equipment		Pour KP 1/2	
16 July	Bench KP 1/2	Cent KP 1/2	Pour KP 3/4	Samples soft
23 July	Bench KP 3/4	Cent KP 3/4	Pour KP 5/6	Good samples
30 July	Bench KP 5/6	Cent KP 5/6	Pour KP 7/8	Good samples
6 August	Bench KP 7/8	Cent KP 7/8	Pour KP 9/10	Good samples
13 Aug.	Bench KP 9/10	Cent KP 9/10	Clean lab.	Holidays
20 Aug.	No testing carried out during this week			
27 Aug.	Retesting of bench equipment		Pour KP11/12	
3 Sept.	Bench KP11/12	Cent KP11/12	Pour KP13/14	Good samples
10 Sept.	Bench KP13/14	Cent KP13/14	Pour KP15/16	Good samples
17 Sept.	Bench KP15/16	Cent KP15/16	END OF KP TEST SERIES	
24 Sept.	Prepare paper for technical transfer conference			
8 Oct.	43rd. Canadian Geotech. Conference			Quebec City
15 Oct.	Compact CC1/2	Cent CC1/2	Continue	MC=30%
22 Oct.	Compact CC3/4	Cent CC3/4	Continue	MC=40%
29 Oct.	Laboratory equipment cleanup		END OF CC TEST SERIES	
5 Nov.	Prepare report for the MInistry of the Environment			

MOE PROJECT 1262 LABORATORY TESTING AND REPORTING SCHEDULES

QUEEN'S UNIVERSITY DEPARTMENT OF CIVIL ENGINEERING

LABORATORY AND CENTRIFUGE
PERMEABILITY TESTS

Date
Technician

16 July 1990

APM/DO

Sample Number: KP1/2

Material Description: CONSOLIDATED KAOLIN

Sample height	<u>5.0</u> cm	Tare	<u>3.99</u>	<u>4.01</u> g
Sample area	<u>28.3</u> cm ²	W+T	<u>261.52</u>	<u>260.12</u> g
Sample volume	<u>141.5</u> cc	D+T	<u>186.02</u>	<u>183.74</u> g
Confining pressure	<u>80</u> kPa	WW	<u>75.50</u>	<u>76.38</u> g
Back pressure	<u>—</u> kPa	W	<u>41.5</u>	<u>42.5</u> %
Head pressure	<u>50</u> kPa	Density	<u>1.82</u>	<u>1.81</u> g/cc

Bench tests: Preconsolidated to ~180 kPa

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
8:45	0	0.15	0	26°	0.20	0	26°
9:45	60	2.00	1.85		2.10	1.90	
11:15	150	4.70	4.55		5.30	5.10	
13:00	255	7.50	7.35		8.65	8.45	
14:30	345	10.35	10.20		11.70	11.50	
16:15	450	13.25	13.10	26°	14.75	14.75	26°
17:15		Sample not kept - left to re-saturate in apparatus. Need further consolidation.					

Permeability coeff:

$$(0.0291) 5.774 \times 10^{-8} (0.87) = 1.46 \times 10^{-9} \text{ m/s}$$

$$(0.0328) 5.774 \times 10^{-8} (0.87) = 1.65 \times 10^{-9} \text{ m/s}$$

Base container:

container mass
tare mass
mass transfer

Sample 1

85.73 g
71.63 g
14.10 g

Sample 2

80.86 g
65.73 g
15.13 g

Centrifuge tests: 17:15 to $T_0 = 25^\circ\text{C}$, $T_{avg} = 28^\circ\text{C}$, $T_c = 0.832$

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
11:15	0	71.63	0	26°	65.73	0	26°
14:15	180	87.52	15.89	28°	84.12	18.29	28°

Permeability coeff:

$$(0.00832) 3.607 \times 10^{-8} (0.832) = 2.65 \times 10^{-9} \text{ m/s}$$

$$(0.0163) 3.607 \times 10^{-8} (0.832) = 3.05 \times 10^{-9} \text{ m/s}$$

QUEEN'S UNIVERSITY DEPARTMENT OF CIVIL ENGINEERING

LABORATORY AND CENTRIFUGE
PERMEABILITY TESTS

Date 23 July 90
Technician Rm/bo

Sample Number: KP 3/4

Material Description: CONSOLIDATED KAOLIN

Sample height	<u>5.0</u> cm	Tare	<u>4.00</u>	<u>3.90</u>	g
Sample area	<u>28.3</u> cm ²	W+T	<u>264.36</u>	<u>269.72</u>	g
Sample volume	<u>14.5</u> cc	D+T	<u>190.39</u>	<u>199.17</u>	g
Confining pressure	<u>80</u> kPa	WW	<u>73.97</u>	<u>70.85</u>	g
Back pressure	<u>—</u> kPa	W	<u>39.7</u>	<u>35.3</u>	%
Head pressure	<u>50</u> kPa	Density	<u>1.84</u>	<u>1.86</u>	g/cc

Bench tests: REG KAOL TO ~ 200 kPa

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
8:10	0	0.50	0	25°	0.10	0	25°
9:05	35	1.75	1.25		1.25	1.15	
11:00	150	3.75	3.25		4.30	4.20	
13:00	270	5.90	3.40	25°	7.60	7.50	25°
14:30	360	7.90	7.40		10.55	9.95	
16:40	490	10.55	10.05		13.30	13.20	
19:00	640	14.30	14.00		16.25	16.15	
23:00	810	18.55	17.75	26°	21.35	21.75	26°

Permeability coeff: $(0.0214) 5.774 \times 10^{-8} = 1.15 \times 10^{-9} \text{ m/s}$
 $(0.0269) 5.774 \times 10^{-8} = 1.35 \times 10^{-9} \text{ m/s}$

Base container:	Sample 1	Sample 2
container mass	<u>87.6</u> g	<u>87.81</u> g
tare mass	<u>71.63</u> g	<u>55.72</u> g
mass transfer	<u>15.0</u> g	<u>22.0</u> g

Centrifuge tests: 26/1/90
 $T_1 = 26^\circ$ $T_{avg} = 28^\circ$ $(T_c = 0.832)$

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
10:30	0	71.63	—	26°	65.72	—	26°
14:00	210	82.69	11.06	28°	77.83	12.10	28°

Permeability coeff: $(0.05267) 3.607 \times 10^{-8} = 0.832 = 1.58 \times 10^{-9} \text{ m/s}$
 $(0.05762) 3.607 \times 10^{-8} = 0.832 = 1.73 \times 10^{-9} \text{ m/s}$

QUEEN'S UNIVERSITY DEPARTMENT OF CIVIL ENGINEERING

LABORATORY AND CENTRIFUGE
PERMEABILITY TESTS

Date 30 July 90
Technician DC

Sample Number: KP 5/6

Material Description: CONSOLIDATED KAOLIN

Sample height	<u>5.0</u> cm	Tare	<u>4.03</u>	<u>4.01</u>	g
Sample area	<u>28.3</u> cm ²	W+T	<u>274.30</u>	<u>272.86</u>	g
Sample volume	<u>141.5</u> cc	D+T	<u>205.90</u>	<u>203.72</u>	g
Confining pressure	<u>100</u> kPa	WW	<u>68.34</u>	<u>69.14</u>	g
Back pressure	<u>—</u> kPa	W	<u>33.6</u>	<u>34.6</u>	%
Head pressure	<u>50</u> kPa	Density	<u>1.91</u>	<u>1.90</u>	g/cc

Bench tests:

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
11:30	0	0.25	0	26°	0.20	0	26°
13:00	90	2.25	2.00		2.10	1.90	
14:10	160	3.80	3.55		3.60	3.40	
15:15	225	5.25	5.00		4.90	4.70	
16:00	270	6.30	6.05		5.85	5.65	
17:20	350	8.10	7.85		7.50	7.30	
18:30	420	9.55	9.30	26°	9.05	8.85	26°
19:30	480	10.95	10.70		10.25	10.05	
Permeability coeff:		$(0.0223) 5.774 \times 10^{-8} (0.87) = 1.12 \times 10^{-9} \text{ m/s}$ $(0.0209) 5.774 \times 10^{-8} (0.87) = 1.05 \times 10^{-9} \text{ m/s}$					

Base container:	Sample 1	Sample 2
container mass	<u>82.42</u> g	<u>75.84</u> g
tare mass	<u>71.63</u> g	<u>65.73</u> g
mass transfer	<u>10.81</u> g	<u>10.11</u> g

Centrifuge tests: $t_0 = 13:15$, $T_0 = 26^\circ$, $T_{avg} = 28^\circ$, $T_c = 0.832$

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
13:15	60	73.85	2.25	28	68.04	2.31	28°
17:15	240	80.67	9.04	28	74.83	9.10	28°
Permeability coeff:		$(0.03767) 3.607 \times 10^{-8} (0.832) = 1.13 \times 10^{-9} \text{ m/s}$ $(0.03792) 3.607 \times 10^{-8} (0.832) = 1.14 \times 10^{-9} \text{ m/s}$					

QUEEN'S UNIVERSITY DEPARTMENT OF CIVIL ENGINEERING

LABORATORY AND CENTRIFUGE
PERMEABILITY TESTS

Date 6 Aug 90
Technician JD

Sample Number: KP 7/8

Material Description: CONSOLIDATED KAOLIN

Sample height	<u>5.0</u> cm	Tare	<u>4.00</u>	<u>3.96</u>	g
Sample area	<u>28.3</u> cm ²	W+T	<u>279.73</u>	<u>268.57</u>	g
Sample volume	<u>121.5</u> cc	D+T	<u>214.8</u>	<u>196.68</u>	g
Confining pressure	<u>100</u> kPa	WW	<u>65.13</u>	<u>71.89</u>	g
Back pressure	<u>—</u> kPa	W	<u>30.7</u>	<u>37.3</u>	%
Head pressure	<u>50</u> kPa	Density	<u>1.95</u>	<u>1.87</u>	g/cc

Bench tests:

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
11:30	0	0.10	0	27°	0.15	0	27°
12:00	30	0.65	0.55	27	0.90	0.75	27
14:00	90	1.80	1.70	26	2.35	2.20	26
15:05	155	3.00	2.90	25°	4.00	3.85	25°
16:30	270	5.20	5.10	25	6.95	6.80	25
17:30	360	6.70	6.80	24	9.20	9.05	24
18:30	450	8.05	7.95	24	10.65	10.50	24°

Permeability coeff: $(0.0189) 5.774 \times 10^{-9} \times 0.879 = 0.96 \times 10^{-9} \text{ m/s}$
 $(1.0250) 5.774 \times 10^{-9} \times 0.879 = 1.27 \times 10^{-9} \text{ m/s}$

Base container:	Sample 1	Sample 2
container mass	<u>80.04</u> g	<u>76.25</u> g
tare mass	<u>71.63</u> g	<u>63.75</u> g
mass transfer	<u>8.41</u> g	<u>10.72</u> g

Centrifuge tests: $t_0 = 12:00, T_0 = 25^\circ, T_{avg} = 27^\circ, T_c = 0.85$

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
13:30	90	72.8	3.18	27°	69.62	3.91	27°
15:00	180	77.86	6.23	27°	73.19	7.46	27°

Permeability coeff: $(0.0346) 3.607 \times 10^{-9} (0.85) = 1.06 \times 10^{-9} \text{ m/s}$
 $(0.0414) 3.607 \times 10^{-9} (0.85) = 1.27 \times 10^{-9} \text{ m/s}$

QUEEN'S UNIVERSITY DEPARTMENT OF CIVIL ENGINEERING

LABORATORY AND CENTRIFUGE
PERMEABILITY TESTS

Date
Technician

13 Aug '90
DQ

Sample Number: KP 9/10

Material Description: CONSOLIDATED KACLIN

Sample height	5.0	cm	Tare	3.96	4.02	g
Sample area	28.3	cm ²	W+T	272.81	267.21	g
Sample volume	141.5	cc	D+T	263.75	194.85	g
Confining pressure	100	kPa	WW	69.06	72.36	g
Back pressure	—	kPa	W	34.6	37.4	%
Head pressure	50	kPa	Density	1.7	1.86	g/cc

Bench tests: T = 25°

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
10:00	0	0.85	0	25	0.30	0	25
11:00	60	2.35	1.50		1.70	1.40	
12:00	120	3.85	3.00		3.15	2.85	
13:00	180	5.40	4.55		4.45	4.15	
14:00	240	6.75	5.90		5.80	5.50	
15:30	330	8.95	8.10		7.90	7.60	
17:00	420	11.20	10.35	25°	9.95	9.65	25°
Permeability coeff:		(0.0247) 5.774×10^{-8}			(0.889) 1.27×10^{-9} m/s		
		(0.02298) 5.774×10^{-8}			(0.889) 1.18×10^{-9} m/s		

Base container:	Sample 1	Sample 2
container mass	82.41 g	75.63 g
tare mass	71.63 g	63.72 g
mass transfer	10.78 g	9.91 g

Centrifuge tests: $t_0 = 11:00$ $T_r = 25^\circ$ $T_{avg} = 27^\circ$ $T_c = 0.85$

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
12:00	60	74.33	2.70	27°	68.23	2.50	27°
14:00	180	79.68	8.05	28°	72.72	6.99	28°
Permeability coeff:		(0.04472) 3.607×10^{-8}			0.85) 1.37×10^{-9} m/s		
		(0.03833) 3.607×10^{-8}			1.85) 1.19×10^{-9} m/s		

QUEEN'S UNIVERSITY DEPARTMENT OF CIVIL ENGINEERING

LABORATORY AND CENTRIFUGE
PERMEABILITY TESTS

Date 3 Sept 1990
Technician JD

Sample Number: KP 11/12

Material Description: CONSOLIDATED KAOLIN

Sample height	<u>5.0</u> cm	Tare	<u>3.99</u>	<u>3.97</u> g
Sample area	<u>28.3</u> cm ²	W+T	<u>264.60</u>	<u>275.65</u> g
Sample volume	<u>14.15</u> cc	D+T	<u>197.01</u>	<u>208.11</u> g
Confining pressure	<u>100</u> kPa	WW	<u>71.54</u>	<u>67.54</u> g
Back pressure	<u> </u> kPa	W	<u>37.1</u>	<u>33.1</u> %
Head pressure	<u>50</u> kPa	Density	<u>1.87</u>	<u>1.92</u> g/cc

Bench tests: T = 20°

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
11:30	0	1.00	0	20°	0.50	0	20°C
12:30	60	2.15	1.15		1.80	1.30	
14:00	150	3.80	2.80		3.65	3.15	
15:30	240	5.50	4.50		5.50	5.00	
17:00	330	7.30	6.30		7.40	6.90	
18:00	390	8.40	7.40		8.70	8.20	
19:00	450	9.55	8.55	20°	10.05	9.45	20°
—							

Permeability coeff: $(0.0210) 5.774 \times 10^{-8} (1.0) = 1.21 \times 10^{-9}$ m/s
 $(0.0190) 5.774 \times 10^{-8} (1.0) = 1.10 \times 10^{-9}$ m/s

Base container:	Sample 1	Sample 2
container mass	<u>80.35</u> g	<u>75.53</u> g
tare mass	<u>71.03</u> g	<u>65.73</u> g
mass transfer	<u>8.72</u> g	<u>9.80</u> g

219195
Centrifuge tests: $\omega = 9.45$ $T_0 = 20^\circ C$ $T_{eq} = 22^\circ C$ $T_c = 0.953$

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
10:45	60	73.88	2.25	21	67.89	2.16	21°
13:45	240	80.80	9.05	22	74.18	8.45	22°

Permeability coeff: $(0.0377) 3.607 \times 10^{-8} (0.953) = 1.30 \times 10^{-9}$ m/s
 $(0.0352) 3.607 \times 10^{-8} (0.953) = 1.21 \times 10^{-9}$ m/s

QUEEN'S UNIVERSITY DEPARTMENT OF CIVIL ENGINEERING

LABORATORY AND CENTRIFUGE
PERMEABILITY TESTS

Date 10 Sept '90
Technician DD

Sample Number: KP 13/14
Material Description: Consolidated Kaolin

Sample height	<u>5.0</u> cm	Tare	<u>3.98</u>	<u>4.02</u> g
Sample area	<u>28.3</u> cm ²	W+T	<u>270.70</u>	<u>277.90</u> g
Sample volume	<u>141.5</u> cc	D+T	<u>199.76</u>	<u>212.12</u> g
Confining pressure	<u>100</u> kPa	WW	<u>70.94</u>	<u>65.78</u> g
Back pressure	<u> </u> kPa	W	<u>36.2</u>	<u>31.6</u> %
Head pressure	<u>50</u> kPa	Density	<u>1.88</u>	<u>1.94</u> g/cc

Bench tests: T = 20°C

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
12:40	0	0	0	20	0	0	20
13:20	40	0.45	0.45		0.40	0.40	
15:30	170	2.55	2.55		3.05	3.05	
17:10	270	6.00	6.0		5.10	5.10	
18:45	365	8.50	8.5		6.95	6.95	
20:00	400	10.50	10.5	20°C	8.45	8.45	21°
22:00	500	13.66	13.66		10.89	10.89	
07:00	1000	26.20	26.2	18°C	21.00	21.0	18°C
Permeability coeff:		$(0.0244) 5.774 \times 10^{-8} (0.988) = 1.28 \times 10^{-9}$ $(0.01946) 5.774 \times 10^{-8} (1.0988) = 1.11 \times 10^{-9}$					

Base container: Sample 1
 container mass 85.22 g
 tare mass 11.03 g
 mass transfer 13.52 g

Sample 2
 container mass 76.76 g
 tare mass 65.73 g
 mass transfer 11.03 g

Centrifuge tests: to = 9 Am T₀ = 17°C T_{avg} = 18°, T_c = 1.051

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
10:30	90	74.60	2.97	18°	68.03	2.30	18°
13:30	180	77.5	5.84	19°	70.30	4.57	19°
Permeability coeff:		$(0.03244) 3.697 \times 10^{-8} (1.051) = 1.23 \times 10^{-9}$ $(0.02954) 3.697 \times 10^{-8} (1.051) = 1.12 \times 10^{-9}$					

QUEEN'S UNIVERSITY DEPARTMENT OF CIVIL ENGINEERING

LABORATORY AND CENTRIFUGE
PERMEABILITY TESTS

Date 17 Sept
Technician SD

Sample Number: KP 15/10
Material Description: Consolidated Kaolin

Sample height	<u>5.0</u> cm	Tare	<u>3.99</u>	<u>4.00</u> g
Sample area	<u>28.3</u> cm ²	W+T	<u>267.14</u>	<u>271.55</u> g
Sample volume	<u>141.3</u> cc	D+T	<u>194.83</u>	<u>201.57</u> g
Confining pressure	<u>100</u> kPa	WW	<u>72.36</u>	<u>69.98</u> g
Back pressure	<u>—</u> kPa	W	<u>37.9</u>	<u>35.4</u> g
Head pressure	<u>50</u> kPa	Density	<u>1.86</u>	<u>1.84</u> g/cc

Bench tests:

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
12:00	0	-0.20	0	17°C	0	0	17°C
14:30	30	0.30	0.5		0.60	0.60	
15:30	90	1.45	1.65	17°C	1.75	1.75	17°C
16:45	165	2.85	3.05		3.05	3.05	
17:20	200	3.60	3.80	17°C	3.80	3.80	17°C
18:00	240	4.30	4.50		4.50	4.50	
19:50	330	6.10	6.30		6.20	6.20	
21:25	465	8.40	8.60	17°C	8.60	8.60	17°C
Permeability coeff: $0.01845 (5.12 \times 10^{-8}) = 1.07 \times 10^{-9}$ $T_c = 1.077 \quad K = 1.15 \times 10^{-9}$							

Base container:	Sample 1	Sample 2
container mass	<u>80.40</u> g	<u>74.55</u> g
tare mass	<u>71.62</u> g	<u>65.75</u> g
mass transfer	<u>8.77</u> g	<u>8.82</u> g

18/9/90
Centrifuge tests: $t_0 = 11:25$ $T_c = 13^\circ C$ $T_{avg} = 15^\circ$ $T_c = 1.135$

Time	ΔT min	Sample No 1			Sample No 2		
		inflow	ΔV cc	T °C	inflow	ΔV cc	T °C
12:25	60	72.55	1.92		67.4	1.75	15°C
14:3	180	77.35	5.72	16°C	70.97	5.24	16°C
Permeability coeff: $0.03178 (3.607 \times 10^{-8}) (1.135) = 1.30 \times 10^{-9}$ $0.0291 (3.607 \times 10^{-8}) (1.135) = 1.19 \times 10^{-9}$							

QUEEN'S UNIVERSITY DEPARTMENT OF CIVIL ENGINEERING

CENTRIFUGE PERMEABILITY TESTS

Date 15 Oct 90

Technician P

Centrifuge Operating Radius 0.35 m

Material Description: CC 1/2 Compacted clay 31% w.c.

Sample height	<u>5.0</u> cm	Tare	<u>40.1</u>	<u>3.79</u>	g
Sample area	<u>28.0</u> cm ²	W+T	<u>271.73</u>	<u>269.25</u>	g
Sample volume	<u>140</u> cc	D+T	<u>208.22</u>	<u>206.66</u>	g
Confining pressure	<u>100</u> kPa	WW	<u>63.51</u>	<u>62.62</u>	g
Head pressure	<u>60</u> kPa	W	<u>31.1</u>	<u>30.9</u>	%
Centrifuge Speed	<u>300</u> rpm	Density	<u>1.91</u>	<u>1.89</u>	g/cc

Time	ΔT min _{hr}	Sample No 1		t °C	Sample No 2		t °C
		mass transfer cc			mass transfer cc		
11:40	0	IN	Σout	12	IN	Σout	12
13:40	2	2.9/2	N/A	14	2.9/2	N/A	14
15:40	4	—	—		—	—	
17:40	6	1.9/2	0.55	15	1.9/2	0.70	15
19:40	8	—	—		—	—	
22:40	11	14/2	0.85	15	14/2	1.28	15

SUMMARY:

Centrifuge speed 300 RPM

Induced pressure 60.5 kPa

Temperature (avg.) 15 °C

Time of test run 11 hrs

Quantity of flow: Sample 1 0.85 cc; Sample 2 1.25 cc

Coefficient of permeability 5.84×10^{-11} m/s

Temperature correction factor 1.135

Corrected hydraulic conductivity 6.63×10^{-11} m/s

QUEEN'S UNIVERSITY DEPARTMENT OF CIVIL ENGINEERING

CENTRIFUGE PERMEABILITY TESTS

Date 22 Oct 90

Technician AT

Centrifuge Operating Radius 0.35 m

Material Description: Tests cc 3/4 Compacted at 38% wc

Sample height	<u>5.0</u> cm	Tare	<u>4.03</u>	<u>4.00</u>	g
Sample area	<u>28.0</u> cm	W+T	<u>258.83</u>	<u>263.11</u>	g
Sample volume	<u>140</u> cc	D+T	<u>188.53</u>	<u>192.17</u>	g
Confining pressure	<u>100</u> kPa	WW	<u>70.30</u>	<u>70.94</u>	g
Head pressure	<u>60</u> kPa	W	<u>38.1</u>	<u>37.7</u>	%
Centrifuge Speed	<u>300</u> rpm	Density	<u>1.82</u>	<u>1.85</u>	g/cc

Time	ΔT min	Sample No 1		t °C	Sample No 2		t °C
		mass transfer cc			mass transfer cc		
9:45	0	1N	Σout	14°	1N	Σout	14°
14:00	4 1/4	0.6/2	1.55	15	0.6/2	0.50	15
19:00	9 1/4	1.8/2	1.18	15	1.8/2	1.05	15
23:00	13 1/4	1.2/2	1.80	15	1.2/2	1.61	15
END TEST							

SUMMARY:

Centrifuge speed 300 RPM Induced pressure 60.5 kPa
 Temperature (avg.) 15 °C Time of test run 13.25 hrs
 Quantity of flow: Sample 1 1.80 cc; Sample 2 1.61 cc
 Coefficient of permeability 7.74×10^{-11} m/s
 Temperature correction factor 1.135
 Corrected hydraulic conductivity 8.78×10^{-11} m/s

ABSTRACT

Experience with commercial testing of clay liner samples for permeability evaluation has shown that standard laboratory permeability tests are subject to leakage problems which can effect the order of magnitude of the results. Furthermore, these tests typically take a week or more to complete and are, therefore, inadequate as field control tests. Physical modelling of various geo-environmental problems in a geotechnical centrifuge was initiated at Queen's University, Civil Engineering Department, in 1988 and it became apparent that the behaviour of clay liners was one of the problems for which centrifuge modelling was well suited. A dedicated 0.5m radius centrifuge was constructed, principally for long term behavioural studies of clay liners but which could also be used for control testing. This paper outlines recent research on the use of the 0.5m radius centrifuge for accurate control testing for clay liner permeability.

The test results are presented in three phases. The first phase used commercial kaolin clay samples prepared by consolidation into a specially designed permeability apparatus. This apparatus was designed for both bench and centrifuge use and allowed a direct comparison of the two methods. The centrifuge method was found to be efficient and reliable. The second phase of this research used a highly impervious compacted clay liner material in the Queen's University 3m radius geotechnical centrifuge. A methodology for accurate clay liner control testing in the centrifuge was developed. The third phase of testing was carried out to examine some longer term permeability variations in compacted liners as a preliminary evaluation of the usefulness of the 0.5m radius centrifuge for liner performance modelling.

The results of this research demonstrate that a geotechnical centrifuge can be used to provide accurate control testing for clay liner permeability. The 0.5m radius centrifuge is relatively inexpensive and sufficiently mobile for field operations and can provide same day liner permeability results in most cases.

INTRODUCTION

A number of researchers and consultants have had experience with clay liner permeability testing in the laboratory and in the field and the general consensus appears to be that liner leakage testing is wrought with problems (see for examples, Chapuis (1990a), (1990b); Quigley (1990); Mitchell (1990)).

Leakage errors in the testing apparatus and the long time required to obtain a satisfactory test result are the two major concerns in laboratory control testing. Field testing is not useful for hydraulic conductivities less than 10^{-9} m/s. A geotechnical centrifuge offers an alternative, relatively rapid and problem free method of evaluating clay liner leakage. A major problem with the specification of centrifuge models as a primary means of commercial liner permeability testing is the limited availability of geotechnical centrifuges. To alleviate this problem, the author has developed a 0.5m radius centrifuge for mobile testing. This paper presents the results of liner leakage testing carried out in this centrifuge.

The research is divided into three phases. Phase 1 research was conducted in the 0.5m radius centrifuge using a consolidated commercial white kaolin clay which was mixed at 100% water content (by dry weight) and consolidated into the permeability testing apparatus. The purpose of phase 1 research was to carry out a sufficient number of bench permeability and centrifuge permeability tests on saturated uniform clay to determine whether the two methods give similar results. Phase 2 research was carried out in the 3m radius centrifuge. The purpose of phase 2 research was to compare the results of triaxial permeability tests on a relatively impervious compacted clay to liner leakage model testing in a moderate sized geotechnical centrifuge. Phase 3 research used the same compacted clay at various moisture contents to carry out a preliminary evaluation of the 0.5m radius centrifuge for use in evaluation of the long term field performance of clay liners and was in progress at the time of writing of this paper.

A prototype clay liner will be overlain by landfill materials which may become saturated with liquids and, over a long period of time, liner leakage may occur. This worse case condition (or any other operational condition) can be modelled in a geotechnical centrifuge. Such centrifuges have been used world-wide for geotechnical physical model testing for the past two decades and are recently being used for research into other civil engineering problems, including environmental engineering problems. In its simplicity, the centrifuge simulates gravitational forces by induced centripetal forces so that a small model may experience prototype stresses and prototype flow and fracture phenomenon. The induced simulated gravity is given by

$$i = r\omega^2/g \quad (1)$$

where i is the liner scale factor, r and ω are the centrifuge radius and speed, respectively, and g is the earth's gravitational constant. For a detailed review of geotechnical centrifuge applications, the reader is referred to Schofield (1980).

The total and effective stresses at all similar points in the model and prototype liners will be identical but the hydraulic gradient across the model liner will be increased by the modelling scale factor. If, for example, a prototype liner of 2m thickness is supporting an overlying 20m head of water, the hydraulic gradient is 10. If a model is designed at a scale factor of $\lambda = 35$, the 57mm thick model would then have an hydraulic gradient of 350 and one day of testing in the centrifuge at $\lambda = 35$ would produce λ^2 days or 3.35 years of prototype per unit area leakage. In fine grained soils Darcy's Law is considered to be applicable over a wide range of gradients (Goodings, 1985).

TEST METHODS

Most methods of measuring permeability of soils involve potential variations and errors. Variations develop in the preparation of most soil samples and errors result from equipment leakages. To carry out a meaningful statistical evaluation of the centrifuge method of clay liner permeability testing it was necessary to develop a leak-proof apparatus in which both bench and centrifuge permeability tests could be carried out under similar conditions on the same samples of a uniform and reproducible clay soil. A saturated consolidated commercial kaolin clay was selected, due to both uniformity and order of magnitude of permeability, as the most suitable clay material. Clay samples for bench permeability testing were preconsolidated to 250 kPa. During a test the sample is surrounded by a silicon rubber membrane and a silicon oil pressure seal of 100 kPa to prevent any possibility of leakage. The hydraulic head applied across the 50mm thick sample was 50 kPa, creating a nominal gradient of 102 and a seepage pressure of about 50 kPa. Over a three month test period a total of 16 independent tests were carried out.

The phase 1 samples remained in the permeability apparatus during transfer from bench to centrifuge and the boundary stress conditions were similar in each test. The centrifuge induced hydraulic gradient across the sample, however, is 163 and the seepage pressure is 80 kPa. Thus the flow rate in the centrifuge is about 1.6 times faster than in the bench test. Never-the-less, the test conditions in both methods are considered closely similar. The test time in the centrifuge was about 3 to 4 hours compared with 6 to 8 hours in the bench tests. The mass of water in the catchment container was measured after one hour of spinning and again at the end of the test. The one hour check point served the purpose of determining whether any consolidation or other "initial phenomenon" were taking place in the centrifuge. In most cases the N hour mass transfer was very close to N times the one hour mass transfer.

In order to compare centrifuge leakage models with triaxial permeability testing, phase 2 testing included double membrane, back pressured triaxial permeability tests on a local illite clay material. A standard Proctor compaction test on this clay gave a maximum dry density of 1.37 g/cc at an optimum water content of 35.5%. The material was stored at this water content and was subjected to standard Proctor compaction to form samples which were subsequently trimmed for permeability testing. After testing the used materials were remixed with the original batch and stored for further testing. Two triaxial cells with back pressured systems (Bishop & Henkel, 1962) were newly assembled, platens were polished and leakage testing of the systems was carried out before the permeability testing was begun. In total, six acceptable tests were carried out over a two month period. This is an average of less than two tests per cell-month, mainly because the system required considerable attention and repair during that time period.

The Queen's 3m radius centrifuge is described by Mitchell (1986) and Figure 1 shows the apparatus developed for liner modelling. The liner model is nominally 50mm thick, and is trimmed to fit snugly in a double thickness membrane encased by a perspex ring. The overlying landfill materials are simulated by a known mass of lead shot overlying a porous plastic disk placed on the top of the liner model. Double thickness filter paper and a porous stone underly the model. Stand pipe arrangements are used to create the water pressure and the confining pressure, which both increase as the simulated gravitational force increases in flight. The confining pressure is maintained at 35 kPa above the water pressure in order to effect a tight contact between the liner model and the rubber membrane. Phase 2 testing was carried out at a scale factor of $\lambda = 35$ with the model representing a 1.7m thick prototype liner. The centrifuge induced hydraulic gradient was 420.

TEST RESULTS

The phase 1 test data is summarized on Table 1. It can be noted that the earliest samples, KP 1 to 4 showed relatively high permeabilities because the preconsolidation pressure was below the desired level of 250 kPa. These samples also gave apparent permeabilities from the centrifuge method which are 1.3 to 1.8 times higher than in the bench test. This is due, no doubt, to consolidation under the simulated gravitational stresses induced in the centrifuge. In this case the effective vertical stress is given by

$$\sigma_v^1 = (z\lambda + iz \sigma_w)g \quad (2)$$

where z is the sample thickness, g is the gravitational constant, σ is the sample density, λ is the scale factor (a/g), i is the induced hydraulic gradient and σ_w is the

density of water

The value of σ_v^1 in the centrifuge model is then calculated to be about 120 kPa. The applied confining stress in the early test was 80 kPa and this would also have contributed to sample consolidation. Subsequent samples were all consolidated to a vertical effective stress, σ_v^1 , of 250 kPa and a confining stress of 100 kPa was used in subsequent tests. It can be seen from Table 1 that subsequent tests (samples KP5 to KP16) provided a fairly consistent set of permeability data. All test data was plotted to obtain the best fit slope of the volume change vs. time line from which the permeability was calculated. The data on Table 1 clearly shows that the 0.5m centrifuge can be used effectively and efficiently to evaluate the permeability coefficient (hydraulic conductivity) of a consolidated clay material.

The results of the phase 2 triaxial permeability testing are contained in Table 2. All samples for which results are tabulated were back pressured to 300 kPa and subjected to an hydraulic gradient of 40. This laboratory testing was carried out at 20°C. From the data it is estimated that the mean permeability value is close to 2.3×10^{-11} m/s with individual test values from 0.3 to 1.3 times the average value. For material evaluation, this data seems reasonably acceptable although the scatter is quite significant.

Phase 2 liner leakage model tests were carried out over periods varying from five hours to ten hours. During some tests the centrifuge was stopped every two hours to check the mass transfer of water by weighing the catchment container (± 0.005 g). Mass transfer quantities were in the order of 0.1 g/hr and the variance found during the two hour interval tests was generally less than 20%. Table 3 shows the data from all of the centrifuge liner leakage model tests carried out. The average leakage rate, from the data on Table 3, is 0.10 cc/hr with a maximum individual test variance of 20%. The water temperature in the centrifuge liner model apparatus increased 0.5°C above the constant laboratory temperatures of 20°C during the first hour or two of spinning at 108 RPM and then remained constant throughout the remainder of the test. The calculated coefficient of permeability, from the average leakage rate is 2.2×10^{-11} m/s. With standard temperature correction, the hydraulic conductivity is estimated to be 2.0×10^{-11} m/s. This value is remarkably close to the average obtained from the triaxial permeability testing but the centrifuge data is more consistent than the triaxial data. This provides some confidence in individual liner control tests carried out by centrifuge modelling.

The compacted liner samples used in phase 2 are more dense than the consolidated samples of phase 1 such that there would be no consolidation during centrifuge liner leakage model tests on compacted samples.

CONCLUSIONS AND RECOMMENDATIONS

From the test data reported, it is concluded the centrifuge model liner leakage testing gives more consistent results for a low permeability compacted soil than triaxial permeability testing. The latter testing is subject to both technical difficulties and leakage risks. It is concluded that a centrifuge liner leakage model can provide realistic liner performance evaluation and that the hydraulic conductivity obtained from such a model will be closely similar to the average values found from good quality triaxial permeability testing.

The main advantages of centrifuge liner leakage models over any permeability tests are:

- (1) Realistic modelling of stress conditions in the liner.
- (2) Elimination of leakage provides more consistent results.
- (3) Elimination of induced hydraulic fracturing.
- (4) Rapid evaluation for construction control testing.
- (5) Greater potential for modelling liner performance.

A complete specification for accurate control testing for clay liner permeability using the 0.5m radius centrifuge has been prepared. This machine is relatively inexpensive and provides a one day control test result in most cases. It is recommended that the centrifuge method of liner leakage control testing be approved for use on liner clay liner construction projects. Further research on liner performance modelling is also recommended.

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Sample No	Saturated density g/cc	BENCH TEST		CENTRIFUGE TEST	
		test time min.	hydraulic conductivity m/s x 10 ⁻⁹	test time min.	hydraulic conductivity m/s x 10 ⁻⁹
KP1	1.82	450	1.46	180	2.65
KP2	1.81	450	1.65	180	3.05
KP3	1.84	810	1.10	210	1.58
KP4	1.88	810	1.35	210	1.73
KP5	1.91	480	1.12	240	1.13
KP6	1.90	480	1.05	240	1.14
KP7	1.95	420	0.96	180	1.06
KP8	1.87	420	1.27	180	1.27
KP9	1.90	420	1.27	180	1.37
KP10	1.86	420	1.18	180	1.19
KP11	1.87	450	1.21	240	1.30
KP12	1.92	450	1.10	240	1.21
KP13	1.88	1100	1.28	180	1.23
KP14	1.94	1100	1.11	180	1.12
KP15	1.86	465	1.15	180	1.24
KP16	1.89	465	1.15	180	1.11

Table 1 - Phase 1 Test Results Summary

Test No	Test Time (days)	hydraulic conductivity m/s X 10 ⁻¹¹	Model No	Run time (hrs)	Hydraulic conductivity (m/s X 10 ⁻¹¹)
LPTX2	9	3.3	LPCM1	5	2.0
LPTX3	8	0.8	LPCM2	7	2.2
LPTX4	7	0.9	LPCM3	8	2.2
LPTX5	8	5.3	LPCM4	6	2.6
LPTX6	12	1.1	LPCM5	10	1.8
			LPCM6	8	2.5

Table 2 - Phase 2 Triaxial Tests Table 3 - Phase 2 Centrifuge Models

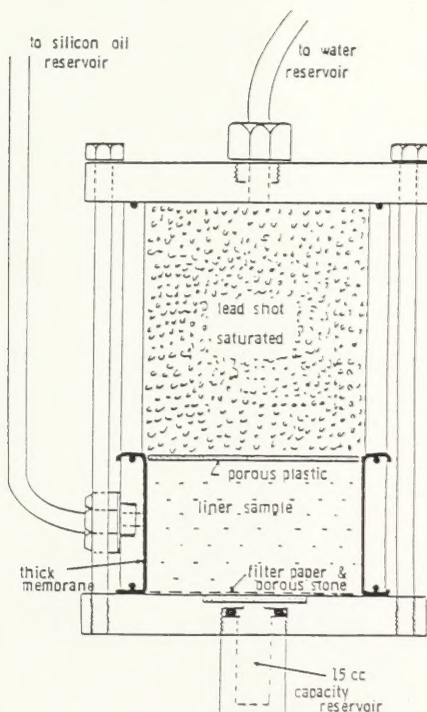


Figure 1 - Drawing of the Centrifuge Liner Model Apparatus

